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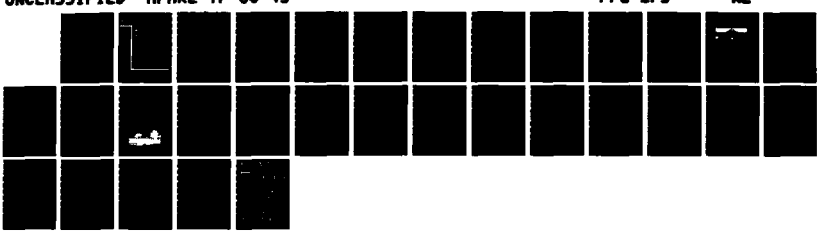

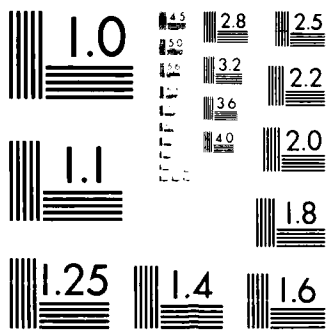

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INTEGRATING A HEAD-UP DISPLAY WITH DOME VISUAL SIMULATION TECHNOLOGY

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December 1986
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THOMAS H. GRAY, Acting Technical Advisor
Operations Training Division

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When viewing a real planar image displayed in a dome through an aircraft Head-Up Display (HUD) focused for "infinity," diplopia and parallax problems render the HUD useless as an aiming or training device. Since HUDs are essential to high-fidelity training in a simulator, this problem must be addressed and resolved. Two potential solutions were investigated: (a) three-dimensional (3-D) scene projection inside the dome, and (b) insertion of a newly designed and fabricated external decollimating lens over the exit lens of the HUD. Three-dimensional imagery resolved the diplopia problem, but unacceptable parallax still remained. The decollimating lens removed the double imagery and parallax problems, but had one major side effect: shrinkage of the HUD's total field of view by approximately 12%, as determined by theodolite readings. It is concluded that 3-D head/eye-tracked dome displays, with mathematical correction for parallax, have a potential for use with unmodified HUDs. An external lens is the most cost-effective means of making a standard aircraft HUD usable in a dome display, but further research should be pursued to determine the effects, if any, of the diminished image on training effectiveness.

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Reviewed and submitted for publication by

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This publication is primarily a working paper. It is published solely to document work performed.

SUMMARY

The Air Force Human Resources Laboratory, Operations Training Division, is developing a visual system for advanced tactical air combat simulation. As part of the development program, an F-16A Block 15S cockpit with a Head-Up Display (HUD) is being installed in a 24-foot-diameter dome display system. Three informal experiments were performed to determine how to achieve visual integration of the HUD symbology with the computer-generated imagery of the world beyond the cockpit. These experiments were developed and conducted with the goal of achieving high fidelity and cost effectiveness. The first experiment determined that an aircraft HUD collimated to "infinity" could not be used with a dome display. The next two experiments explored modifications that would make the HUD a useful training device in the dome. Results of the second experiment suggest that head/eye-tracked, three-dimensional displays, with mathematical corrections for parallax in the computer-generated image, could be very effective with unmodified HUDs, particularly in small domes. The third experiment established that placing an external decollimating lens over the HUD exit lens cured the double imagery and parallax problems, but caused approximately 12% shrinkage of the HUD's total field of view. It has not yet been determined what effect, if any, this shrinkage would have on the training effectiveness of a simulator.

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PREFACE

Considering various design options, this investigation contributes to the development of cost-effective flight simulation display technology. To investigate the training effectiveness of various visual parameters (such as brightness, contrast, and resolution) upon pilot performance in simulated air-to-air, air-to-ground, and terrain-following fighter aircraft training, it is mandatory that information presented via the Head-Up Display (HUD) be seen singly and clearly against the computer-generated visual display of out-of-cockpit scenes.

Specifically, the F-16A HUD serves two critical functions: (a) It presents information formerly available only on dials and gauges within the cockpit, each of which previously had to be read separately, and (b) it provides sighting and targeting cues. Research and development for effective combat mission training depends upon the proper visual integration of HUD information and aiming with the task-related visual display of the aerial and terrain environment. The experiments herein deal with the provision of HUD symbology in concert with adequate visual scenes for combat mission training. Thus, this effort addresses a critical Tactical Air Force requirement in the development of a low-cost, transportable combat mission trainer.

The authors wish to thank John Van Hoogstrate and Ralph Fisher of McDonnell-Douglas Aircraft Company for their cooperation and help in designing the lens used to modify the HUD image. We would also like to acknowledge the assistance of the Singer/Link Division engineering support team, particularly Earlin Ward, in setting up these experiments at Williams Air Force Base.

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INTEGRATING A HEAD-UP DISPLAY WITH DOME VISUAL SIMULATION TECHNOLOGY

I. INTRODUCTION

In order to "blend in" the pilot's view of the world on actual real-life missions, Head-Up Displays (HUDs) were designed with "infinity" optics. That is, HUDs were so designed that their images would appear to originate at "infinity." Light from HUD symbology appears to come from a great distance away and is collimated; i.e., the light rays are practically parallel. Thus, when a pilot fixates on a target through the HUD in the real world, all the information he needs is presented by the HUD and he does not have to shift his gaze and change his visual accommodation by refocusing on dials and gauges within the cockpit.

In the past, simulators that had "infinity" windows were used so there would be no conflict with HUD imagery. But because such "infinity" windows were too dim, too expensive, and presented a relatively small field of view (FOV) when used singly, they have fallen from favor. A new press is on for wider and brighter simulated FOVs. The use of smaller dome displays (under 24 feet in diameter) is seen as a means to these ends.

In order to practice carrying out mission objectives, the pilot in training needs to integrate the visual information displayed on a HUD with information contained in computer-generated representations of the world front-projected onto the interior surface of a dome. Yet, a problem emerges when the pilot no longer has a long-distance view of the outside world, as occurs with smaller dome simulators.

II. EXPERIMENT 1. SUBJECTIVE EVALUATIONS OF A HEAD-UP DISPLAY WITH A PROJECTED REAL IMAGE DISPLAY

The first section of this paper reports an informal "experiment" performed over 3 days in February 1986, at the Operations Training Division, Air Force Human Resources Laboratory (AFHRL) facility at Williams Air Force Base, Arizona. The experiment was intended to provide support for simulator design decisions. The purpose of this first "quick and dirty" experiment was to confirm or deny a negative theoretical answer to the question, "Can the F-16A HUD be used in a simulator involving dynamic real images[1] front-projected onto the surface of a 24-foot-diameter dome?"

Method

Apparatus

By means of a carousel projector, a static real image of a runway was projected onto a small (30 x 40 inches), flat, white screen located approximately 12 feet in front of an observer. Figure 1 is a reproduction of the simple runway scene which originally had been computer-generated. Mounted on a table directly in front of the seated observer was an F-16A HUD manufactured by G.E.C. Electronics (formerly Marconi Avionics Limited) of Rochester, Kent, England. Light from the HUD is collimated; light rays are almost parallel, as if originating at

[1] A real image occurs when the rays of light from an object actually converge to form an image that can be seen on a screen from which rays of light appear to diverge.

a far distance. The focal distance of the HUD was reported to be 1,750 inches or nearly 146 feet. A schematic of the fairly complicated, Standard Cursive, green, F-16 HUD imagery, which combines flight information with weapon aiming capabilities, is presented in Figure 2.

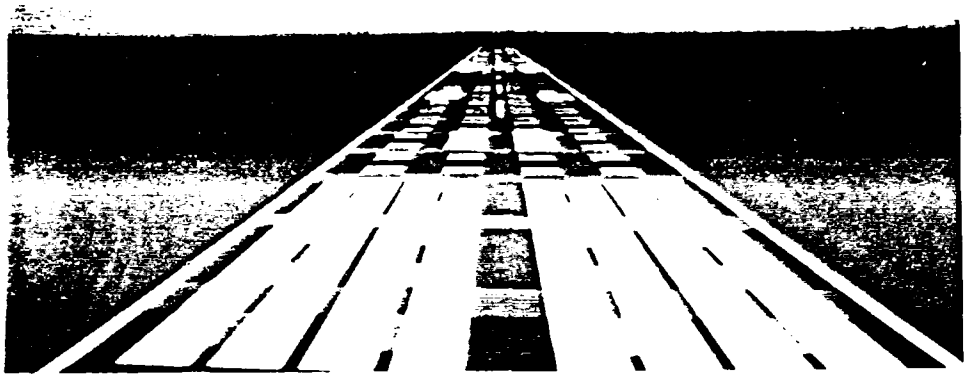

Figure 1. Reproduction of the Projected Runway Scene.

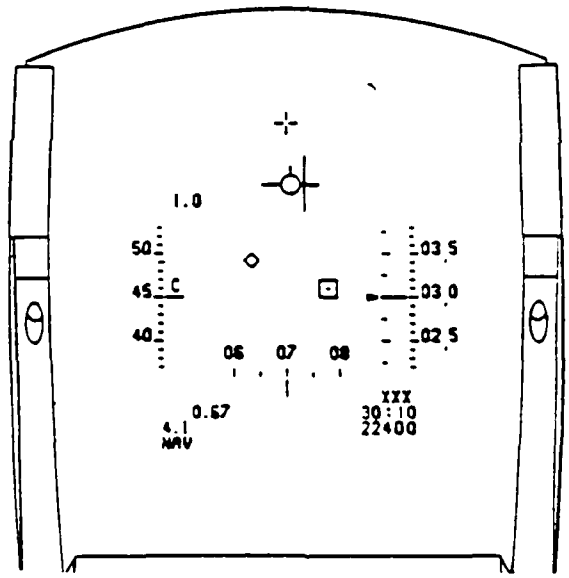

Figure 2. Schematic of Standard Head-Up Display (HUD) in the F-16A.

Subjects

The observer group was a diverse sample consisting of 19 individuals ranging in age from 26 to 59, with a mean age of 40 years. Although 42% wore corrective lenses, all subjects had 20/20 or better visual acuity. In terms of professional employment, 26% of the subjects were or had recently been Air Force fighter pilots (four pilot/instructors and one deputy commander), 42% were engineers (three systems engineers, two mechanical engineers, two electrical engineers, and one engineering manager), and 32% were psychologists (five experimental and one engineering). From an academic perspective, the subject sample was well educated, with several holding more

than one baccalaureate degree, at least 21% holding masters (MS), and 32% holding doctorates (PhDs). More importantly, 58% of the subject group had flight and piloting experience: In addition to the five Air Force pilots, the group contained one civilian pilot/instructor, two former Air Force pilots, and three former civilian/commercial pilots.

Procedures

Each subject was seated at the table and asked to adjust the brightness of the HUD until it approximated the brightness of the sky above the runway in the projected scene. To elicit an initial response (i.e., to get the subjects talking), subjects were asked to describe what they saw. Subjects were then asked the following questions, and their responses were recorded.

1. When you are focused on the runway, what does the HUD look like?

2. When you are focused on the HUD, what does the runway look like?

3. Where is the HUD located in depth relative to the runway? Do you see the HUD in front of, in the same plane as, or in back of the runway?

4. Please close one eye. Now where do you see the HUD located relative to the runway?

5. You are presently looking at a static display of a runway. In a simulator that display would be dynamic. In your opinion, can we use this HUD in the dome simulator?

Results

In response to question 1 ("When you are focused on the runway, what does the HUD look like?"), subjects described the HUD as (in rounded percentages):

- 63% doubled or partially doubled
- 21% blurred, blurry, or out-of-focus
- 16% mostly OK or pretty good

In response to question 2 ("When you are focused on the HUD, what does the runway look like?"), subjects described the runway as:

- 32% doubled
- 58% blurred, fuzzy, messy, or out-of-focus
- 10% OK, I guess

Of the two subjects who did not report doubled or degraded images in response to either of the above questions, one complained during the trial that the combined imagery was "uncomfortable" and the other later reported experiencing "slight eyestrain." These two subjects were the eldest among the observer group.

In response to question 3 ("Where is the HUD located in depth relative to the runway?"), subjects reported seeing the HUD as:

- 58% in back of, behind, or farther away than the runway
- 5% in the same plane as the runway
- 32% in front of the runway
- 5% can't tell

In response to question 4, whether they observed the combined displays monocularly, subjects saw the HUD as:

- 74% in the same plane as the runway
- 21% in front of the runway
- 5% can't tell

The most important question was question 5, which dealt with the issue of whether or not the F-16A HUD, which provides a collimated image, could be used in a simulator with a planar projected real image 12 feet from the subject's eye. Responses were:

- 95% No (including: "I don't see how"; "Not on your life"; and a vociferous "No way!"
- 5% Qualified Yes ("I don't see why not.")

Responses to this last question evidenced considerable unanimity of opinion. The greatest variance among the 18 observers responding negatively to the question appeared to be in the degree to which they expressed their conviction.

Discussion

Two major issues deserve consideration at this point. The first issue deals with the representativeness of the subject group. The second issue deals with the correspondence between anticipated results based on theory and the actual responses received, particularly as influenced by the nature of the experiment (i.e., "quick and dirty").

The most important subgroup of the subject sample was the five experienced Air Force pilots. When focusing on the runway (question 1), one pilot saw the HUD image as fuzzy and out-of-focus, whereas two pilots saw parts of the HUD imagery as doubled. The remaining two pilots not only stated that the HUD was doubled, but were able to specify the distances between those doubled images. When focusing on the HUD (question 2), two pilots reported that they saw the runway as doubled, whereas three pilots saw the runway as blurred or fuzzy and partly out-of-focus.

When locating the HUD in space binocularly (question 3), two pilots saw the HUD as behind the runway, two saw it in front, and one pilot simply could not tell where the HUD was located. When viewed monocularly (question 4), the HUD was unanimously depicted as being in the same plane as the runway image. Unanimity was again reached in response to the last question (question 5). All pilots definitely believed that the F-16A HUD could not, and should not, be used with a 24-foot-diameter dome simulator display. In brief, the pilots, a subgroup of five, responded much as the entire sample of 19 subjects had responded, particularly if "outlier" responses are purged. With the exception of age, the subject sample can be held as sufficiently representative of individuals for whom the simulator is being designed.

Because the present effort was performed hastily, without regard for the rigorous controls and design sophistication required by formal experimentation, the preceding findings must be regarded as tentative, as indicative rather than conclusive. Prior to experimentation, the theoretical position of the authors had been that observers would probably experience substantial conflict among convergent and accommodative cues from the planar projection 12 feet away and depth cues associated with the collimated HUD image (Graham, 1951, 1965; Grether & Baker, 1972). This led to the belief that a complicated HUD would not visually blend or be integrated with a real image projected so close to the observer. The data collected in Experiment 1 fully support that earlier belief.

Before experimentation, it was predicted that most observers would experience some double imagery/diplopia (Hochberg, 1971). While focused on the runway (question 1), the majority of subjects (63%) did, in fact, report some diplopia of the HUD imagery. The prediction was in error, however, when subjects focused on some portion of the HUD image (question 2). That is, only a minority of subjects (32%) reported seeing the runway as doubled, whereas the majority (58%) reported the runway as blurred, fuzzy, or out-of-focus. There appears to be a greater tendency to maintain fusion with an actual scene than with schematic or symbolic imagery. This the authors had not anticipated.

Previous studies at this Laboratory (Bell & Ciuffreda, 1985; Woodruff, Hubbard, & Shaw, 1985) and elsewhere (Kraft & Shaffer, 1978) have reported that collimated displays, such as used in the In-Line Infinity-Optics System windows, provide an observer with an increased sense of "volume," depth of field, and/or realism. In fact, some experimenters have implied that collimated light may be a monocular cue to distance and depth (Braunstein, 1976; Schlosberg, 1941). Thus, it was anticipated that subjects would see the HUD image as behind (or farther away than) the real image of the runway both binocularly (question 3) and monocularly (question 4). Subjects responded more idiosyncratically than expected, however. Although a majority of observers (58%), when viewing with both eyes, did see the HUD image behind the runway, a sizeable minority (42%) did not. Moreover, when the displays were viewed monocularly, not one single subject responded as anticipated: The majority (74%) saw the HUD and the runway in the same plane. Thus, any strong predictive relationship between collimated displays and depth perception is called into question. Perhaps the depth aspect of collimation operates only in the absence of any other depth cues, such as apparent superposition.

Based on the findings in Experiment 1, we may tentatively conclude that the F-16A HUD, as it now stands, cannot be used in combination with a planar projection of a real image in the 24-foot-diameter dome. Without modification, the HUD would induce, at least, eyestrain and, at most, considerable diplopia among pilot trainees.

At least three modification possibilities present themselves: (a) three-dimensional (3-D) presentation of the real image on the dome surface, (b) projection of a HUD image onto the surface of the dome, or (c) decollimation of the HUD. It is reasonable to wonder if a stereoscopic or 3-D presentation of the world outside the cockpit on the nearby screen would be sufficient to overcome the double vision and blurring. Since no studies could be unearthed that provided an answer, option 1 will have to be determined by experimentation. An application of option 2, projection of the HUD image onto a dome surface, is presently underway in the Navy's Visual Training Research Simulator at the Naval Training Systems Center in Orlando, Florida. If option 3, decollimation of the HUD, is pursued, it is safe to assume that the F-16A HUD should be modified such that light from it appears to match the distance between the trainee's eyepoint and the dome surface. Although precise decollimation would probably require extensive rebuilding of the HUD display unit, severe modification and functional destruction of this expensive piece of equipment may not be necessary.[2] It was determined that a second experiment would be performed and that inquiries into the means of decollimating a HUD would be pursued.

III. EXPERIMENT 2. SUBJECTIVE EVALUATIONS OF A HEAD-UP DISPLAY WITH BOTH TWO- AND THREE-DIMENSIONAL PROJECTIONS

The goal of this second experiment was twofold. The first purpose was to corroborate, if possible, the findings of Experiment 1 under slightly different conditions. That is, since a

[2]Berg, T. Personal communication with author, Philipp Peppler, on 14 March 1986, regarding the F-18 simulator at Lemoore Naval Air Station, CA.

rather simple background scene was combined with a fairly complicated HUD display in the first experiment, the reverse was to be attempted here. The second purpose was to investigate the potential use of a HUD presentation combined with a 3-D visual display on the dome surface. Specifically, the second goal addressed the issue: "Will a stereoscopic or 3-D dome display overcome the diplopia introduced by a nearby planar display so that an unmodified HUD may be used in a dome simulator?"

Method

Apparatus

This experiment was intended to compare or contrast subjects' responses to a planar projection of a static real image similar to that used in Experiment 1 with responses to a 3-D image, both evaluated while looking through a HUD. Thus it was necessary to devise an experimental setup which permitted easy switching from one display to the other so that both display types could be presented in one trial in the same facility as used previously. To present the 3-D display, two carousel projectors were used to project circularly polarized, 30- by 40-inch similar images on a silver projection screen located approximately 12 feet in front of the observer. The silver screen was used to preserve the polarization of the dual images. While viewing the images, subjects wore Polaroid II paper glasses which contained circularly polarizing filters (right eye, clockwise; left eye, counterclockwise). Matching filters were mounted on the right and left eye slides as presented in the left and right projectors. Then the left eye saw only the image on the left, and the right eye saw only the image on the right. Before each trial, each subject's interpupillary distance (IPD) was measured using a commercially available Topcorn PD Meter. For 3-D viewing, images from the two projectors were manually separated by the subject's approximate IPD, using a scale mounted at the top of the silver screen for reference. This technique made the subject's left eye and right eye visual axes parallel, and thereby provided infinity convergence cues. For the planar presentations, only one projector was used, and the subjects wore no glasses.

Figure 3 is a reproduction of the slide used singly in the planar presentation and as one of two slides in the 3-D presentation. The somewhat complicated real-life scene illustrated in Figure 3 focuses on a very large ejection seat training apparatus about 400 feet away, with volleyball and basketball courts in the near foreground.

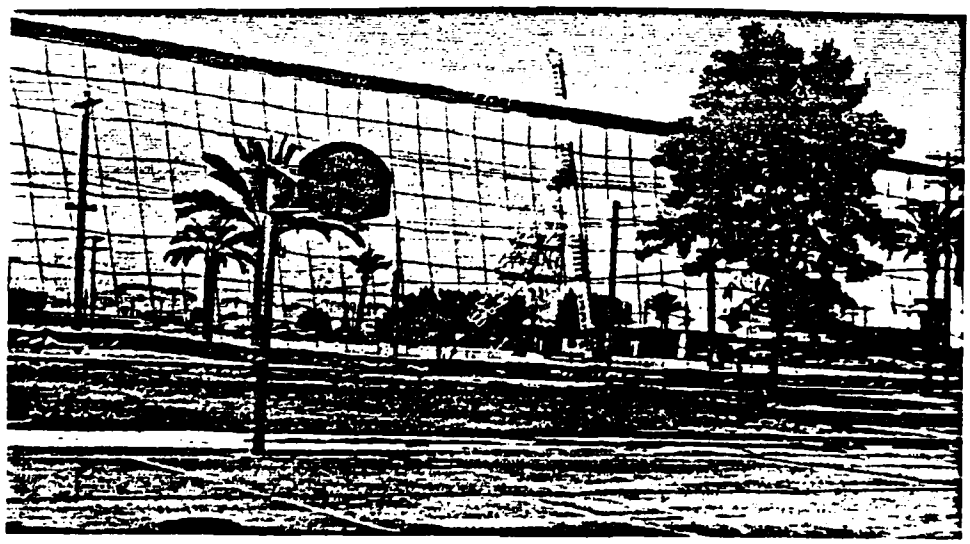

Figure 3. Reproduction of Slide Presented in Two and Three Dimensions.

Mounted on a table directly in front of the seated observer was the same HUD used previously, except this time the red standby (or manual) reticle was used. Figure 4 presents a schematic of this rather simple image, which consisted of a 2-mil[3] pipper and two red, concentric, broken-line circles. This reticle is used for manual weapons delivery.

Subjects

The subject group was a sample consisting of 21 individuals ranging in age from 25 to 55, with a mean age of 37 years. Although all had 20/20 vision, 29% wore corrective lenses. Thirty-three percent of the subject sample were Air Force officers; the others were civilians. Educationally, 19% were PhDs, 19% held MS degrees, and 57% held baccalaureates. Among the subject sample were five present and two former Air Force pilots in addition to three civilian pilots or pilot/instructors, producing a total of 48% of the subject sample with moderate to extensive flight experience. Interpupillary distances of the subject group ranged from 60 to 70 millimeters, with a mean of 65 millimeters and a standard deviation of 2.81 millimeters.

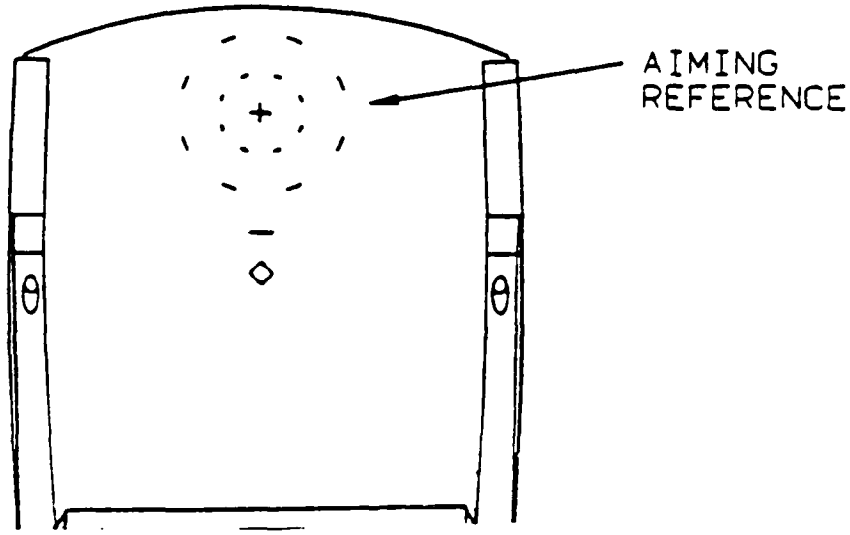

Figure 4. Schematic of Manual Reticle of the Head-Up Display.

Procedures

After each subject's IPD was determined, the experimenter adjusted the two projectors such that the images were separated by a distance which matched, as closely as possible, the subject's IPD and then turned off one projector. The subject was seated at the table and asked to adjust the brightness of the HUD image near to the brightness of the three-legged, boom-type ejection seat training apparatus in the scene. To elicit an initial response, the subject was asked, "What do you see when you look [at the scene] through the HUD?" The experimenter's questions are reproduced in Figure 5. After Part I, the experimenter turned on the second projector while the subject donned the polarized paper glasses. As is evident in Figure 5, Part I replicated

[3]A mil is a unit of angular measurement originally used in artillery and equal to 1/6400 of a complete revolution. Nowadays the term is used to mean a milliRadian; so, in contemporary parlance, a mil subtends .0573 degree or 3.438 minutes of arc. Easier to remember: At 1,000 feet, 1mR subtends 1 foot.

Experiment 1, and Parts II and III dealt with the use of a 3-D visual display in conjunction with the F-16A HUD.

Part I. What do you see when you look through the HUD?

1. Focusing on the ejection seat apparatus, how does the HUD appear?

2. Focusing on the central pipper of the HUD, how does the scene appear?

3. Where in space is the HUD located relative to the scene?

4. Close one eye. Now where do you see the HUD relative to the scene?

5. Can this HUD, without modification, be used with a flat planar projection such as this scene or even the dome display?

Part II. Please put on these glasses. Are they comfortable?

1. Looking at the scene alone, not through the HUD, what do you see?

2. Look at the scene through the HUD and focus on the ejection seat apparatus. How does the HUD appear?

3. Focusing on the central pipper of the HUD, how does the scene appear?

4. Where is the HUD located in space relative to the scene?

5. Close one eye and tell me where the HUD appears in space.

6. a. Would you say that this HUD, without modification, could be used with a stereoscopic presentation of this sort?

b. Do you have any reservations about this?

Part III. Now move your head laterally, not rotationally (demonstrate) a very small amount, about an inch, to the right. Now move it about an inch to the left. Go back and forth a couple of times if you wish. Now move the same way up and down.

1. Does anything change as you move your head?

2. What changes or appears to happen?

3. How would you describe the relationship between the amount of your head movement and the amount of change you see?

Figure 5. Open-Ended Questions and Directions for Experiment 2.

Results

Part I. Planar or Two-Dimensional (2-D) Presentation

In response to question I-1 ("Focusing on the ejection seat apparatus, how does the HUD appear?"), all subjects indicated that they had some visual difficulty, and 19 subjects (91%) directly mentioned doubling of the HUD image. Specific responses (in rounded percentages) were:

91%	(62%)	Double
	(19%)	Double and out-of-focus/blurry and double
	(10%)	Double, comes and goes/clear, changes to double
	(10%)	Blurry/defocused

In response to question I-2 ("Focusing on the pipper of the HUD, how does the scene appear?"), five subjects (24%) reported progressive changes for the worse the longer they regarded the scene. Those and other responses were:

	(43%)	Double
71%	(10%)	Blurry changed to double
	(5%)	Out-of-focus changed to double
	(14%)	Can't bring into focus/out-of-focus
	(5%)	Clear changed to hard-to-focus
19%	(14%)	Blurry (badly or terribly)
	(10%)	Fairly clear/normal

Question I-3 ("Where in space is the HUD located relative to the scene?") elicited the following responses:

(38%)	In back/behind/sort of behind/floats in back
(5%)	Can't tell -- maybe even
(57%)	In front/closer to me

After closing one eye, subjects responded to a similar question (I-4) as follows:

(24%)	Even/in the same plane
(71%)	In front/even closer
(5%)	Can't tell

A succinct, unanimous "No" was the response of 21 subjects (100%) to question I-5, which asked if the HUD could be used without modification with a flat, planar projection such as the present scene or a dome display. Five individuals added gratuitous comments. One quietly said it would be "very disorienting"; two asserted it would "drive me crazy" or "drive a person nuts." The other two insightfully recommended "closing one eye" or "use only with one-eyed pilots."

Part II. A Three-Dimensional Presentation

After putting on the polarizing glasses and looking at the projected scenes, omitting the HUD, all subjects experienced depth. In response to question II-1 ("Looking at the scene alone, not through the HUD, what do you see?"), 29% of the subjects' responses indicated that they felt it was not a very good 3-D presentation, as illustrated below:

	(71%)	Depth/3-D
	(14%)	"Some" depth/"Some" 3-D/"Some" stereo
29%	(14%)	"Slight" depth/"Poor" 3-D

While focusing on the ejection seat apparatus through the HUD, responses to question II-2 ("How does the HUD appear?") revealed the following:

	(48%)	Single and clear
95%	(29%)	Good and clear
	(19%)	Single
	(5%)	Slight vertical doubling-now clear

A surprising variety of descriptors were elicited in response to question II-3 ("Focusing on the central pipper of the HUD, how does the scene appear?"). Although most mean the same thing, the descriptors were as follows:

76%	(24%)	Single/single and clear
	(33%)	Clear/fine and clear
	(19%)	Fine and normal/OK and in focus/good/good and single
	(19%)	Fairly clear/somewhat clear/much clearer than before
	(5%)	Good - some minor rivalry

While viewing binocularly, when asked where the HUD was located in space relative to the scene (question II-4), subjects responded:

(5%)	In back
(10%)	Even/same plane
(86%)	In front

After closing one eye and viewing the scene monocularly through the HUD, subjects responded to a similar question (II-5) as:

(14%)	Same plane
(81%)	In front/in front closer
(5%)	Can't tell

Responses to question II-6, which asked if the HUD could be used with a 3-D presentation without modification, were as follows:

90%	(52%)	Yes with no reservations
	(38%)	Qualified yes
	(10%)	No

Subjects were also asked if they had any reservations regarding their answers. Although the majority had none, 7 of the 10 individuals responding with a "No" or a qualified "Yes" cited visual parallax or head movement as a problem.[4]

Part III. The Three-Dimensional Presentation, Continued

After translating their heads a small amount from side to side and up and down, 21 subjects unanimously responded "Yes" when asked if they saw anything changing (question III-1).

In response to question III-2 ("What changes or appears to happen?"), all subjects confirmed that the HUD image moved in the same direction as the head movement. That is, the HUD image moved to the right when their heads did, to the left when their heads did, and similarly for up and down. Only one subject briefly considered that the background scene might be moving in the opposite direction, but after more moving and looking, he rejected the idea.

Question III-3, which asked subjects to compare the amount of head movement with the amount of change in the HUD image, elicited much thought and several trials on the part of the

[4]Parallax is defined as the apparent displacement of an object observed due to a change or difference in the position of the observer. As applied here, it means the subjects saw an apparent change in the position of the HUD imagery relative to the visual scene, caused by moving their heads, which provided new lines of sight.

subjects. Fifteen subjects (71%) expressed the relationship of the amount of head movement to the amount of HUD image movement as a ratio. Of these, five subjects stated that the relationship was linear. But some other subjects took an entirely different tack. Using the diameter of the central 2-mil pipper as a reference, six subjects (29%) defined the amount of movement of the HUD image during a 1-inch lateral translation of the head. The two sets of responses in rounded percentages of the total group are:

Ratio Responders (n = 15):

(14%) 2 head:1 HUD/Between 2 head:1 HUD and 4 head:1 HUD
(48%) About 1:1, the same or a comparable amount
(10%) 1 head:3 HUD/1 head:6 HUD

Measurement Responders (n = 6):

(10%) 1 inch = 6 mils HUD movement
(10%) 1 inch = 5 mils/1 inch = 4 to 6 mils HUD movement
(10%) 1 inch = 4 mils/1 inch = 3 or 4 mils HUD movement

Discussion

Part I of this experiment thoroughly confirmed the three most meaningful and most important findings of the first experiment. For example, while focusing on an object in the background in this experiment (question I-1), 91% of the subjects saw the HUD imagery as doubled. This can be compared to 63% for Experiment 1 (question 1). Similarly, while focusing on the HUD, 58% of the subjects saw the background scene as doubled in this second experiment (question I-2). This compares with only 32% who saw the background runway as doubled and 58% who saw it as blurred, fuzzy, messy, or out-of-focus in the first experiment (question 2). When subjects were asked if the F-16A HUD could be used in conjunction with a dome simulator, this experiment (question I-5) elicited a unanimous "No," whereas 95% responded negatively to the same question in the first experiment (question 5).

In terms of locating the HUD imagery in space relative to the location of the projected planar display, the tendency to locate the HUD imagery in front of the other display or closer to the subject was stronger in this experiment than in the first experiment, both binocularly and monocularly. In this experiment (question I-3), for example, when viewing the total scene binocularly, a majority of 57% reported that they saw the HUD in front of the planar projection. This can be contrasted with 32% in the first experiment (question 3). Likewise, when viewing monocularly, 71% placed the HUD imagery in front in this second experiment (question I-4), compared to 21% in Experiment 1 (question 4).

Because this fast, "quick and dirty" second experiment lacked the precision, finesse, and sophistication of formal experimentation (as did the first), it would be inappropriate to attempt to draw conclusions as to why these latter results were obtained. One can point out, however, that the differences in stimulus materials may account for some of the response differences between these two experiments. The first experiment incorporated a complicated HUD display and a simplified, computer-generated image of a runway. This second experiment incorporated the opposite; namely, a simplified HUD reticle and a complicated real-life, planar projected scene.

The greatest claim that can be set forth for Part I of Experiment 2 is that a twofold confirmation was achieved. The first finding confirmed was that combining a HUD display with a flat, 2-D display projected onto a surface 12 feet from the observer will produce at best, fuzzy,

blurry, or out-of-focus images and at worst, diplopia or double imagery for a majority of subjects. The second finding confirmed is that almost all subjects agree that combining an unmodified F-16A HUD with a dome simulator is totally inappropriate.

Part II of Experiment 2 involved presenting a 3-D display in conjunction with the HUD display. Although conclusions must be regarded as strictly tentative due to the informal nature of the experiment, nonetheless evidence indicates that a 3-D presentation will probably solve the diplopia problem found in Experiment 1 and Part I of Experiment 2. The most significant findings of Part II of Experiment 2 are the responses to questions II-2 and II-3: "Look at the scene through the HUD and focus on the ejection seat apparatus. How does the HUD appear?" and "Focusing on the central pipper of the HUD, how does the scene appear?" Not one subject experienced lasting double images or reported seeing blurry, fuzzy, messy, or out-of-focus images for either the HUD display or the 3-D ejection seat scene. Furthermore, these responses were made to a presentation which 29% of the subjects regarded as displaying poor depth properties (question II-1). The reason one subject briefly thought he saw a vertical doubling (in response to question II-2) was probably due to vertical misalignment, since the 3-D displays were set up separately by hand for each subject (Lipton, 1982).

It is perhaps not surprising that the majority of subjects (86%) located the HUD display in front of the 3-D display when viewing the combined displays binocularly. Despite the relatively poor depth effect, these responses could be regarded as reasonable, considering the facts that the HUD display was collimated and focused at "infinity" (in this case, 146 feet) and that the 3-D display focused on the central figure of an ejection seat apparatus photographed from a distance of 400 feet.

What does not appear to be quite so reasonable, however, is that with one projector turned off while viewing monocularly, 81% of the subjects continued to see the HUD display as in front of the polarized projected scene, but this time in 2-D. This is based on responses to question II-5, "Close one eye and tell me where the HUD appears in space." Because the experiments made no attempt to control for order of presentation, such as counterbalancing, it would be inappropriate to test for the significance of differences of the same subjects responding monocularly to a polarized image (81% in front to question II-5) and to an unpolarized image (71% in front to question I-4). The same experimental restriction applies to investigating responses to a similar question asked in Experiment 1 (question 4), in which only 21% of a different subject group reported seeing a different HUD image, also in front of a different 2-D planar projection.

The authors began Experiment 2 with high hopes that a stereoscopic or 3-D presentation would prove to be the solution to the issue of integrating a HUD display with a dome simulator display. These high hopes were dispelled in Part III of Experiment 2 when questions III-1 and III-2 were asked: "Does anything change as you move your head?" and "What changes or appears to happen?" The unanimous discovery that the HUD image moved relative to the visual scene, as did the subjects' heads, revealed that although the diplopia problem might be solved, a new problem had emerged. That problem was parallax. Simply speaking, the parallax problem means that unless the parallax can be corrected, the HUD is useless as an aiming device.

Parallax is the result of the continuously varying perspective which occurs when one moves his head or changes his point of view (Lipton, 1982). When a subject's head moves with respect to the environment, a differential angular velocity exists between his line of sight to a fixated object and his line of sight to any other object in the visual field. This condition of differential angular velocity - or continuously changing perspective of some objects relative to other objects in the visual field - leads to such observations that near objects move against the direction of head movement and far objects move with the direction of head movement (Graham, 1951).

It is curious to note that the observed HUD movement was unanimously observed to move with the direction of head movement, which would indicate a far object. Yet, earlier in Part II, 86% of the subjects had reported that they saw the HUD display as in front of the 3-D display, which would indicate a near, or at least nearer, object according to Graham. Unfortunately, resolution of this apparent contradiction must await further and much more formal experimentation.

It is worth noticing that 30% of the subjects did not hesitate to give specific measurement responses when asked in question III-3 to describe the relationship between the amount of HUD movement and the amount of head movement. The mean of these six subjects' responses was 4.9 mils per 1 inch of head movement, with a standard deviation of 1.02 mil. Although these data are far too skimpy and informally obtained to serve as a basis for generalization, followup formal experimentation appears fruitful. This is particularly so if the dome to which such generalizations would be applied is head-slaved or eye-slaved. That is, it is possible to use a 3-D computer-generated dome display if mathematical correction for head movements can be made to the computer image generation display.

Although the modifications which would have to be made to the present dome display under construction were considered too extensive and too expensive for present application, a 3-D display with parallax correction may turn out to be the only way to go for very small domes such as those with a 10- or 12-foot diameter. In the present study, attention was next turned to option #3 discussed earlier: an investigation into the means of decollimating the F-16A HUD display.

IV. EXPERIMENT 3: THE INSERTION OF A PLANO-CONCAVE LENS AFTER THE EXIT LENS OF THE HEAD-UP DISPLAY DEVICE

Fairly early in this effort, it was discovered that precise decollimation of the HUD would require complete modification of the display unit. That is, total redesign of the system and fabrication of six or seven internal lenses would be required if precise decollimation were mandated. The manufacturer could perform the rebuilding at considerable but not unreasonable cost over at least 5 months. This rebuilding, however, would also render the display unit totally unairworthy and expensive to return to its original configuration for use in F-16 aircraft.

Because of time, cost, and the permanent nature of such a modification, the experimenters decided to explore other means of decollimating the HUD display. They knew that if they failed, a complete modification of the HUD would always exist as a final or ultimate option.

Methods and Results

Experiment 3 differs from the two preceding experiments because it is based on the two stages briefly identified below:

Stage 1. Information and Lens Design: Information about methods to decollimate HUD imagery other than total rebuilding was actively sought. A lens based on that information was designed and fabricated, despite anticipation of some shrinkage of the HUD image.

Stage 2. Measurement of Shrinkage and Estimation of Error: To provide information to estimate the effect of HUD image shrinkage upon pilot trainee performance, the amount of shrinkage produced by the addition of the newly fabricated lens was measured by two different techniques.

Stage 1. Information and Lens Design

While discussing the HUD used in the F-18 simulator at Lemoore Naval Air Station, Mr. Tom Berg stated, "We put a lens on top of the last lens in the HUD. The lens cured the double image and caused the pipper and bogie to line up."[5] That statement led one of the authors on a detective-like chase to find out what kind of a lens and who had made it. He struck paydirt when he reached Mr. Ralph Fisher and Mr. John Van Hoogstrate.[6,7]

To decollimate the HUD, it is necessary to mount a lens on top of the exit lens such that light rays will diverge instead of remaining parallel and such that the HUD imagery will appear to fall on the interior surface of the dome, as does the computer-generated, front-projected scene. That is, light from the HUD must be so focused that it appears to match the distance between the trainee's eyepoint and the dome surface. Figure 6 is a drawing which depicts the distances which needed to be known to compute the necessary focal length, f, of such a lens. Those distances are:

The viewing distance A + C = 137"
The distance from the combining glass to the screen A = 117"
The distance from the eyepoint to the combining glass C = 20"
The distance from the HUD exit lens to the combining glass B = 4"

To determine f, the following relationship must hold. f + C + B = A + C, or in simplified form:

f = A - B = 113"

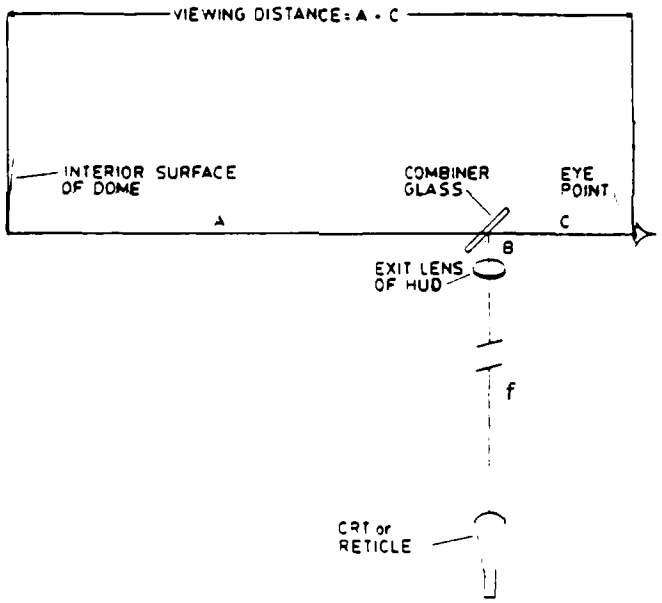

Figure 6. Schematic of Dome Set-Up to Determine Needed Focal Distance.

The placement of a lens with a focal length of 113 inches on top of the exit lens of the HUD causes the HUD image to diverge so it will appear to have originated at the same distance as the dome wall, 117 inches away, when it reaches the combining glass.

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[5]Berg, T., Ibid.

[6]Fisher, R.A., McDonnell-Douglas Aircraft Corporation, St. Louis, MO. Personal communication by telephone with author, Philipp Peppler, on 19 March 1986, about HUD decollimation.

[7]Van Hoogstrate, J., McDonnell-Douglas Aircraft Corporation, St. Louis, MO. Personal communication by telephone with author, Philipp Peppler, on 19, 20, and 26 March 1986, regarding HUD decollimation and lens specifications.

To compute the curvature of the lens to be fabricated with one flat or plane side, the following basic optical formula was used:[8]

$$\frac{1}{f} = (m-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

where: f = the focal length (here = 113")
m = the refractive index of the glass (here = 1.517)
r_1 = radius of the curvature of the flat side of the lens
r_2 = radius of the curvature of other side of the lens

The refractive index, m, was based on the assumption that Grade A material BK7 quality glass with a refractive index of 1.517 would be used in the lens. Since one side of the lens was to be flat, the radius for the curvature of that side was infinity. Hence the reciprocal term, $1/r_1$, becomes zero and drops out. The basic optical formula became:

$$\frac{1}{113} = (1.517 - 1.0)\left(-\frac{1}{r_2}\right)$$

Solving for r_2 = .517 (-1) (113) = -58.48 inches

The importance of the minus sign means that this side of the lens will be a negative/concave lens. Thus, the specifications for the plano-concave lens ordered from the Optical Science Center of the University of Arizona were as follows:

Diameter of lens = 4.97 inches, tolerance + 0 and -.01"
Central thickness = .250 inch, tolerance not critical, $\pm$ .015"
r_1 = infinity, therefore perfectly flat
r_2 = 58.48 inches, tolerance $\pm$ 1%
Wedge factor to be kept less than .005
Reasonably good polishes (no scratches or other visual defects)
No coatings

If the HUD is a wide-angle, holographic-type HUD with dual combiners, a slight tilting of one of the combiners will have to be made. The F-16A has a single combining glass, so no modification was necessary.

Stage 2. Measurement of Shrinkage and Error Estimation

A very high priority at the AFHRL facility at Williams AFB was completion of an F-16 dome research simulator project, of which this investigation was a part. Although disassembly of the HUD had been scheduled for installation into the new dome, luckily the new lens arrived at the laboratory ahead of schedule and the F-16A HUD was available for 3 days. The data cited below are reasonably good estimates, considering the brief time allowed. They are presented principally because they have, at the very least, value as "in the ballpark" figures and permit a comparison of measurement techniques.

The first step in evaluating the new lens was to test the appearance of the HUD image using the Continuously Computed Impact Point (CCIP) bomb pipper and display. Figure 7 presents a

[8]Sumner, R., Optical Science Center, The University of Arizona, Tucson, AZ. Personal communication with author, Philipp Peppler, on 19, 21, and 26 March 1986, regarding the fabrication of a special lens.

schematic of the HUD display in the CCIP mode. This mode was selected as a test of the bottom extremity of the HUD display. The test demonstrated that no part of the bomb fall line was obliterated when the new external plano-concave lens was installed. Even though the total field showed some shrinkage compared to the HUD display without the lens, no imagery was lost.

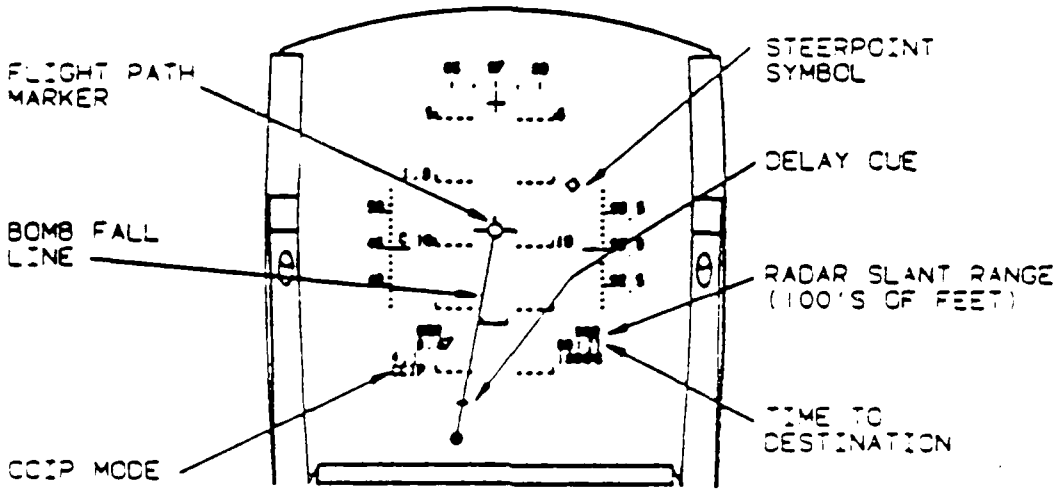

Figure 7. Schematic of the CCIP Mode of the F-16A HUD.

Both of the measurement techniques utilized in this experiment were based on the manual or standby reticle, illustrated in Figure 4. This simple red display contains a 2-mil pipper surrounded by a circle of dashed lines with a radius of 25 mR. The inner circle is, in turn, surrounded by a second circle of dashed lines with a radius of 50 mR. One hundred milliradians below the central pipper is an open diamond-shaped figure which can also be used as a reference (General Dynamics, 1984).

In the initial measurement attempt, a scale marked in quarter-inch units was mounted vertically down the middle of the display screen. The standby reticle counter, located on the front of the HUD display unit, was used to measure the depression angle in milliradians from the gun boresight (zero depression angle being boresighted). So that the HUD image appeared toward the top of the display area, the standby reticle counter was set at 19. Then two subjects each performed four measurement trials. A trial consisted of a series of five visual judgments of the point of intersection of the scale with:

- the top of the outer circle
- the top of the inner circle
- the pipper
- the bottom of the inner circle
- the bottom of the outer circle

Two trials were performed without the new lens; then two trials were performed with the new plano-concave lens installed, curved side down, on top of the exit lens of the HUD. When these visual judgments were completed, the standby reticle counter was reset to 46, which moved the display down toward the center of the screen. This was done to determine if the amount of shrinkage varied in different areas of the lens. The series of four trials were then repeated. The standby reticle counter was again reset to 96, which moved the HUD display even lower on the screen, and the entire process repeated.

Because the HUD image without the new lens induced diplopia, subjects had to make visual judgments under the strain of keeping one eye closed. Subjects complained of difficulty because the HUD image also displayed parallax; that is, the display shifted if the observer moved his head in the slightest. These difficulties undoubtedly introduced error. Similar judgments made

with the new lens inserted on top of the HUD led to no complaints because, of course, there was neither diplopia nor a parallax problem. Should these kinds of visual judgments be attempted again, it would be wise to provide the subject with a head rest and sighting device to stabilize his head and eyepoint.

In data analysis, three values were computed which reflected distances of 50 mRs for each trial. These were averaged for each subject over the two trials with the external plano-concave lens, then the two trials without the lens, at each of three screen positions. By comparing the mean visual judgment with and without the new lens, the average percent shrinkage could be computed as displayed in Table 1. While the average absolute shrinkage (in milliradians reduced over a distance of 50 or 100 mRs) could have been derived, the large variance between and within subjects displayed in Table 1 discouraged further data manipulation. Instead, another measuring technique was investigated.

Table 1. Percent Shrinkage as Measured by Visual Judgments

Screen	Subject 1	Subject 2
	%	%
Upper Section	15.9	14.4
Middle Section	15.2	12.7
Lower Section	12.5	11.9
Average	14.5	13.0

A second set of measurements was based on the use of a theodolite, a fairly sensitive instrument used primarily in surveying to measure angles of elevation and azimuth. The focusing element of a theodolite is a very small telescope with crosshairs for centering. Sighted through a separate aperture on the theodolite, three scales display elevation from ground zero, for instance, in degrees, minutes, and seconds. The HUD display was the same manual reticle used in earlier measurements (see Figure 4).

A series of readings were taken with and without the new external plano-concave lens, with the theodolite focused and centered on the red pipper while the standby reticle counter (in mRs) was set at 0, 100, and 200. Because the counter could not be set much beyond 200 (thus moving the pipper and the display farther down the screen), a second set of readings was taken. With the counter set at 150, the theodolite was focused first on the red pipper and then on the diamond figure located 100 mRs below the pipper, producing an equivalent counter setting of 250. For this second set of readings, the theodolite had to be raised to a new position in order to get the diamond in the sight line of the telescope. To complete the second series from the new position, the standby reticle counter was set at 50 mR and readings were taken with and without the new lens, with the theodolite centered on the pipper.

Theodolite readings can be used to determine both percent shrinkage and absolute error in mRs. Since a radian equals 57.295 degrees, 1 milliradian equals .057295 degree and 100 mRs equals 5.7295 degrees. Based solely on the HUD with the new lens, theodolite readings taken at 100-mR intervals can thus be used to compute shrinkage relative to 5.7295 degrees. At the same counter setting, differences between readings with and without the external lens can be converted directly into mRs error.

Based on the HUD with the external plano-concave lens in place, Table 2 presents a series of differences between two theodolite readings taken at counter settings representing theoretical separations of 100 mRs. The percent shrinkage was found by dividing these differences by 5.7295 degrees, subtracting the result from 1.00, then multiplying by 100. The seven shrinkage percentages presented in Table 2 have an overall average of 12%.

Table 2. Percent Shrinkage: Theodolite Readings of HUD with New Lens

Focus points	Counter settings	Difference between theodolite readings	Percent shrinkage relative to 5.7295°
Pippers	0 & 100	5.03611°	12.1%
Pippers	0 & 100	5.03083°	12.2%
Pippers	100 & 200	5.08750°	11.2%
Pippers	50 & 150	5.05694°	11.7%
Pippers	50 & 150	5.07222°	11.4%
Pipper/- -	150 & 250 est.	5.00694°	12.6%
Pipper/- -	150 & 250 est.	5.00417°	12.7%

Table 3 presents the differences in decimal degrees found between theodolite readings taken with and without the external lens at the same setting of the standby reticle counter. A plus sign means that the reading made with the plano-concave lens inserted was larger than the reading made without it. The high incidence of positive differences in Table 3 indicates that with progressively higher counter settings, the HUD display with the lens inserted made less of an excursion down the display area than did the HUD display without the lens. With only single pairs of theodolite readings taken at four of the six counter settings investigated, the reader can infer from the irregular increase in error that this form of measurement is not at all free from observer error. Although definitive statements must await repeated measurements with different observers using the theodolite, the overall average of the limited data available suggests an average error across the surface of the display in the neighborhood of 9 mRs.

Table 3. Error Based on Differences between Theodolite Readings

Focus	Counter setting	Difference: Same setting (w/Lens - w/o lens)	Error in mR
Pipper	0	- .0428°	- 0.7
Pipper	50	- .3431°	- 6.0
Pipper	100	+ .6264°	+10.9
Pipper	150	+ .3042°	+ 5.3
Pipper	150	+ .3056°	+ 5.3
Pipper	200	+1.3000°	+22.7
Diamond	250 est.	+ .9722°	+16.9
Diamond	250 est.	+ .9778°	+17.1

Discussion

Despite the care and precision that went into Stage 1 of this experiment, since the measurements and readings of Stage 2 were collected in a rapid manner which lacked the rigor of formal experimentation, once again the measures must be regarded as approximate, and subsequent conclusions can be no more than tentative. The newly designed and fabricated lens, when placed curved side down over the exit lens of the HUD, appears to remove the diplopia/double imagery and parallax problems successfully. It does so, however, at a price. That price appears to be a reduction in the overall size of the HUD FOV by approximately 12%. The HUD symbology and the image projected onto the interior surface of the dome visually blend so well that the shrinkage is not immediately apparent.

Of the two measurement techniques used in Stage 2 to investigate the approximate amount of shrinkage - visual judgments and theodolite readings - the latter appears to hold greater promise because both percent shrinkage and absolute error in mRs can be derived. Many more measurements or readings than are reported here need to be made by several observers at various locations in the HUD FOV. Further, the theodolite should be initially set up to cover the entire HUD field so that it does not need to be moved later. Of particular importance will be determining the increase in absolute error as one moves away from the lens center, both vertically and horizontally. It can be expected that the center of the HUD FOV will be affected relatively little; however, missions in which the pilot trainee must utilize the periphery, particularly for aiming and triggering, may be adversely affected. The amount and nature of the effect of shrinkage of the HUD's FOV on pilot trainee performance is of critical importance for estimating training effectiveness.

Once the HUD is installed and operating within the dome, a quick check of the accuracy of the shrunken reticle could be made. The test is based on: (a) the knowledge that a 100-milliradian change in the setting of the HUD reticle counter subtends an angle equal to 5.7295 degrees (1 10 radian) and (b) computation of the distance subtended by a given visual angle by the formula:

$$\tan \frac{\theta}{2} = \frac{Y/2}{X}$$

where X equals the distance to the interior surface of the dome (137"), Y equals the distance on a vertical surface, and θ is 5.7295^{0}. By substitution and solving for Y, one gets:

$$Y = 2 \times \tan \frac{\theta}{2} = 1\ (137")(.05004) = 13.7112"$$

In practice, the HUD will be set for the manual or standby reticle and the counter set at 0 mRs, and the actual position of the pipper will be identified on the dome wall or a screen. The counter will then be reset to 100 mRs and the new location of the pipper on the dome surface or screen identified. While there may be a need for some correction for curvature of the dome, which will slightly increase the value, if the difference in pipper locations is equal to 13.71", weapons delivery will be accurate. Time did not allow an application of this test in the present effort.

Should the error due to shrinkage prove to be beyond acceptable limits, however, there are a few options available. The first option is to modify the simulator software, adapting it to the pilot trainee's new view of the HUD superimposed on the dome's visual display. Another option would be to have the manufacturer make a slight modification within the HUD unit, specifically to increase the size of the HUD symbology by adding small feedback resistors to the cathode-ray tube system.[9] Care must be used with this option, however, because if the increase is too large, some HUD symbology may "fall off the edge." A third option is the development of additional or substitution lenses which would have the effect of expanding the HUD FOV toward its original size.

V. CONCLUSIONS AND RECOMMENDATIONS

Since these conclusions and recommendations are based on "quick and dirty" experimentation, the caveat that they be regarded as tentative, and indicative rather than conclusive, continues to apply.

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[9]Perkins, D., G.E.C. Electronics, Dallas-Ft. Worth Branch. Personal communication with author, Philipp Peppler, on 25 March 1986.

1. An aircraft HUD, collimated to "infinity," cannot be used with a front-projected dome display, because a doubling of the imagery will probably occur. The doubling is so severe that it appears to mask a parallax problem which also occurs.

2. A 3-D display removes the double imagery but does not remove the parallax problem.

3. If a computer-generated dome display were head/eye-slaved, the possibility exists for correcting the parallax of a 3-D display mathematically through the image generator. This may well be the only way in which very small domes with diameters of 10 to 12 feet can achieve integration of the HUD and dome displays.

4. The addition of an external plano-concave lens, curved side down, on top of the exit lens of the HUD resolves the double imagery and parallax problems, but simultaneously, it occasions a 12% shrinkage of the HUD's FOV.

5. The effect of this shrinkage upon the performance of pilot trainees or subsequent training effectiveness is, as yet, undetermined.

6. The influence of the HUD's reduced FOV on training effectiveness should be tested for several types of missions. In particular, high-drag weapons delivery missions should be investigated because it is anticipated that a maximum negative error due to shrinkage would be manifested with this kind of mission. The effect of a relatively small amount of shrinkage may not be noticeable or significant with air-to-air combat, terrain-following, or low-drag weapons delivery missions.

REFERENCES

Bell, H.H., & Ciuffreda, K.J. (1985). Advanced simulator for pilot training: Effects of collimation on accommodation and vergence (AFHRL-TP-85-27, AD-A159 545). Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

Braunstein, M.L. (1976). Depth perception through motion (pp. 21-29). New York: Academic Press.

General Dynamics Manual (1984, August). F-16A Block S Avionics Systems Manual (Document #16PR3613, pp. 7-84). Fort Worth Division, General Dynamics.

Graham, C.H. (1951). Visual perception. Chapter 23 in S.S. Stevens (Ed.), Handbook of experimental psychology (pp. 870-895). New York: John Wiley and Sons.

Graham, C.H. (1965). Visual space perception. Chapter 18 in Graham (Ed.), Vision and visual perception (pp. 504-542). New York: John Wiley and Sons.

Grether, W.F., & Baker, C.A. (1972). Visual presentation of information. Chapter 3 in Van Cott and Kinkade (Eds.), Human engineering guide to equipment design. Washington, DC: U.S. Government Printing Office.

Hochberg, J. (1971). Perception. Chapter 13 in Kling and Riggs (Eds.), Woodworth and Schlosberg's experimental psychology (3rd ed. pp. 475-505). New York: Holt, Reinhart and Winston.

Kraft, C.L., & Shaffer, L.W. (1978). Visual criteria for out of cockpit visual scenes. In AGARD Conference Proceedings No. 249, Piloted Aircraft Environment Simulation Techniques. Washington, DC: National Aeronautics and Space Administration.

Lipton, L. (1982). Foundations of the stereoscopic cinema (pp. 56-58). New York: Van Nostrand Reinhold Company.

Schlosberg, H. (1941). Stereopsis depth from single pictures. American Journal of Psychology, 54, 601-605.

Woodruff, R.R., Hubbard, D.C., & Shaw, A. (1985). Advanced simulator for pilot training and helmet-mounted visual display configuration comparisons (AFHRL-TR-84-65, AD-A155 326). Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

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